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Editorial

Greenhouse gas contributions and mitigation potential in agricultural regions of North America: Introduction

1. Purpose

The articles in this special issue were assembled following discussions among program leaders and scientists, primarily at a USDA Agricultural Research Service workshop held in Bloomington, MN, USA in September 2002. Our goals for this special issue were (1) to assemble a database on agricultural management effects on soil C sequestration and greenhouse gas emission, (2) synthesize what is known and identify what is not known about the effects of agricultural management on greenhouse gas emission and mitigation potential in different regions of North America, (3) determine major ecoregion differences in how agricultural management might mitigate and contribute to greenhouse gas emission, and (4) present future research needs. Our original intent was to limit our objectives to the USA, but it became evident that much relevant data had already been collected throughout Canada. Therefore, the regions we delineated included the agricultural regions of Canada (Fig. 1). We wanted to include an assessment of information for all of Mexico to obtain a more thorough evaluation for North America, but we were limited in resources to make this assessment. However, an original research report evaluating tillage and cropping system effects on soil organic C sequestration from Mexico was included.

This regional assessment of how agriculture might contribute to and mitigate greenhouse gas emission in North America was viewed as a necessary initial step to eventually conduct a more targeted research approach on the related topics of (1) soil C sequestration, (2) trace gas emission, and (3) environmental quality. The final paper in this issue describes an integrated approach to assess these topics within the USA through a project called Greenhouse Gas Reduction through Agricultural Carbon Enhancement network (GRACEnet).

Overviews of soil C sequestration in both cropland (Lal et al., 1998) and grazing lands (Follett et al., 2001) are available for the entire USA. This special issue, as well as the developing GRACEnet project, are aimed at identifying the regionally specific agricultural management systems that will contribute to a better understanding of how soil organic C sequestration can be maximized, how net global warming potential resulting from agriculture can be minimized, and how whole-ecosystem environmental quality can be optimized with agricultural production goals. This special issue compliments the latest inventory of greenhouse gas emissions and sinks reported for agriculture and forests in the USA (USDA, 2004), which described on a national level, the sources and mechanisms of emission and potential mitigation of the three principle greenhouse gases [carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4)]. Several other recent reports have described the well-documented global increase in concentration of greenhouse gases and their relationship to human activities (IPCC, 2001; Wofsy and Harriss, 2002).

2. Characterization of regions

North America has bountiful natural resources shared among three large countries, Canada, Mexico, and USA (Table 1) that produce abundant agricultural

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Fig. 1. Delineation of five regions in North America for separate assessments of agricultural contributions to and mitigation potential of greenhouse gas emission.

commodities. Farming in the USA is diverse due to a number of factors, including climate, soil, water supply, infrastructure development, and population density. The most recent Census of Agriculture (USDA-NASS, 2002) indicates that of the more than 2 million farms in the USA, primary activities of these farms are distributed as beef cattle (31%), diversified crop (21%), oilseed and grain (16%), aquaculture and diversified animal (11%), fruit and tree nut (4%), greenhouse, nursery, and floriculture (3%), cattle feedlot (3%), dairy cattle and milk (3%), vegetable and melon (2%), hog and pig (2%), poultry and egg (2%), and sheep and goat (2%).

Soil resources and climatic factors play a major role in the type of agriculture practiced in different parts of the continent. Climate, in particular, determines the type and amount of vegetation that occurs naturally and that can be managed. One of the reasons for dividing North America into five major regions was based on climate differences. The boundaries of the five regions were delineated based on ecoregions developed by the United States Forest Service (Bailey, 1995) and by Agriculture and Agri-Food Canada and Environment Canada (Ecological Stratification Working Group, 1995).

Although there is considerable variation in climatic characteristics within each of the regions, they can be broadly categorized (Table 2). Western Canada and northwestern USA are cold in the winter and mild in the summer with potential evapotranspiration (PET) generally exceeding annual precipitation (P). Eastern Canada and northeastern USA are cold in the winter and mild in the summer with PET $<$ P. The southwestern USA is mild in the winter and hot in the summer with PET $\gg$ P. The southeastern USA is mild in the winter and hot in the summer with PET $\approx$ P. The central USA is intermediate in environmental conditions to those of the other regions. Climatic conditions, to a large extent, control steady-state soil organic C levels in North America (Jenny, 1941). In general, soil

Table 1
General agricultural characteristics of three countries in North America

Category	Canada	USA	Mexico
Total land area (Mha)	997[a]	937[a]	196[a]
Human population (millions)	30[a]	260[a]	94[a]
Number of farms (thousands)	247[b]	2129[c]	NA
Farmland (Mha)	68[b]	380[c]	NA
Cropland (Mha)	36[b]	123[c]	16[d]
Cattle and calf inventory (millions)	15.6[b]	95.5[c]	30.5[d]
Hog and pig inventory (millions)	14.0[b]	60.4[c]	16.1[d]
Sheep and lamb inventory (millions)	1.3[b]	6.3[c]	14.8[d]
Layer inventory (millions)	26.3[b]	334.4[c]	142.5[d]
Broiler inventory (millions)	87.4[b]	1389.3[c]	224.5[d]
Turkey inventory (millions)	8.1[b]	93.0[c]	4.9[d]
Arable, permanent cropland (Mha)	46[e]	179[e]	27[e]
Fertilizer use (kg ha^{-1})	54[e]	103[e]	67[e]
Meat production (Tg)	3.3[e]	35.1[e]	3.9[e]
Tractors (thousands)	711[e]	4800[e]	185[e]

NA, not available.
[a] From National Geographic Society (1995).
[b] From Statistics Canada (2001).
[c] From USDA-NASS (2002).
[d] From Statistics Agricultural Bureau (2004) with translation provided courtesy of J.R. Salinas-Garcia.
[e] From World Resources Institute (2004).

organic C increases with increasing precipitation and decreasing temperature, although variation in soil texture, type of vegetation, and drainage modify this generalization, resulting in patchy distribution within the continent (Fig. 2).

Institutional resources necessary to conduct agricultural and environmental research are highly developed in North America (CSRS and UGA, 1994). With the combination of federal and state/provincial support, agricultural experiment stations are widely distributed throughout the entire spectrum of soil and climatic conditions represented in North America (Fig. 3). Although this network of agricultural experiment stations is extensive, their ability to achieve common research objectives is often limited due to the need to individually serve local and diverse clientele, changing targets of high-priority research, lack of formal national and international coordination mechanisms, and limited funding. Federal agricultural experiment stations have an advantage over state/provincial experiment stations, as they do have national program leadership to address and coordinate high-priority research needs across a diverse landscape.

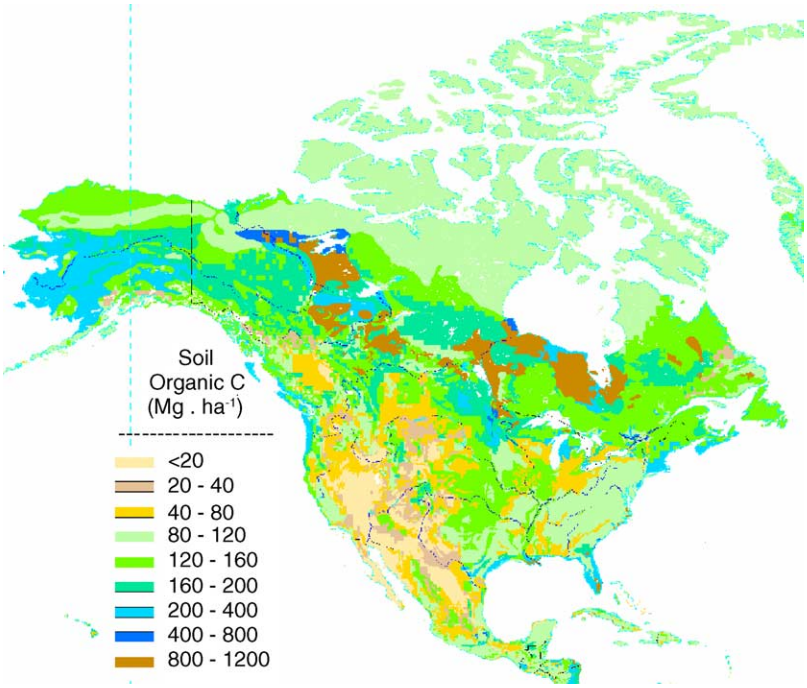

Fig. 2. Geographical distribution of soil organic C to a depth of 1 m in North America (USDA-NRCS, 1997).

Table 2
Environmental characteristics of three major cities within each of six regions of North America

Location	Mean daily temperature (°C)[a]		Mean number of days with precipitation[a]	Mean annual precipitation (mm)[b]
	January–March	July–September		
Western Canada and northwestern USA				
Bismark, ND	−9.7	18.5	94	392
Calgary, AB	−7.3	13.8	101	421
Denver, CO	0.7	20.3	86	391
Eastern Canada and northeastern USA				
Charlottetown, PEI	−6.2	17.3	115	1068
Montreal, QC	−7.3	18.5	157	946
Toronto, ON	−3.7	18.7	145	765
Central USA				
Chicago, IL	1.7	21.5	124	908
Pittsburg, PA	1.0	21.7	150	935
St. Louis, MO	2.8	24.8	112	951
Southwestern USA				
Las Vegas, NV	10.0	27.7	18	105
Phoenix, AZ	13.5	30.7	39	194
San Francisco, CA	11.3	15.7	67	500
Southeastern USA				
Atlanta, GA	8.5	24.8	124	1288
New Orleans, LA	14.7	27.5	122	1569
Tampa, FL	17.0	27.2	116	1114
Mexico				
Acapulco	25.7	27.8	80	1387
Mexico City	14.0	17.5	170	848
Monterrey	16.5	26.7	90	849[c]

[a] From National Geographic Society (1995).
[b] Mean annual precipitation from 1961 to 1990 for sites in USA, from 1885 to 1989 for Calgary, from 1874 to 1989 for Charlottestown, from 1942 to 1989 for Montreal, and from 1951 to 1989 for Toronto (NCDC, 2004) and from 1961 to 1990 for sites in Mexico (www.theweather-network.com).
[c] Precipitation from Tampico.

3. Summary

This set of articles should be considered a current evaluation of soil C sequestration and greenhouse gas emission from unique agricultural regions in North America. Each of the five regional papers provides a review of available data within the region and relevant research pertaining to agricultural contributions to and mitigation of greenhouse gas emission. The paper by Del Grosso et al. (2005) presents a regional modeling analysis within the USA of nitrous oxide (N_2O) emission under different agricultural management scenarios. Their estimates indicate that N_2O emission is the dominant contributor to net global warming potential from agriculture in all regions of the USA. Corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production systems were estimated to emit the greatest amount of N_2O of all major cropping systems. Their model analyses suggest that conservation-tillage management of cropland would emit a lower quantity of N_2O from soil to the atmosphere and sequester a greater quantity of C from the atmosphere to the soil than under conventional tillage. Improving fertilizer N management to better synchronize inorganic N availability with crop demand was suggested as a way to further reduce N_2O emission and net global warming potential of typical agricultural systems in the USA.

The paper by Liebig et al. (2005) represents the relatively large land area of western Canada and

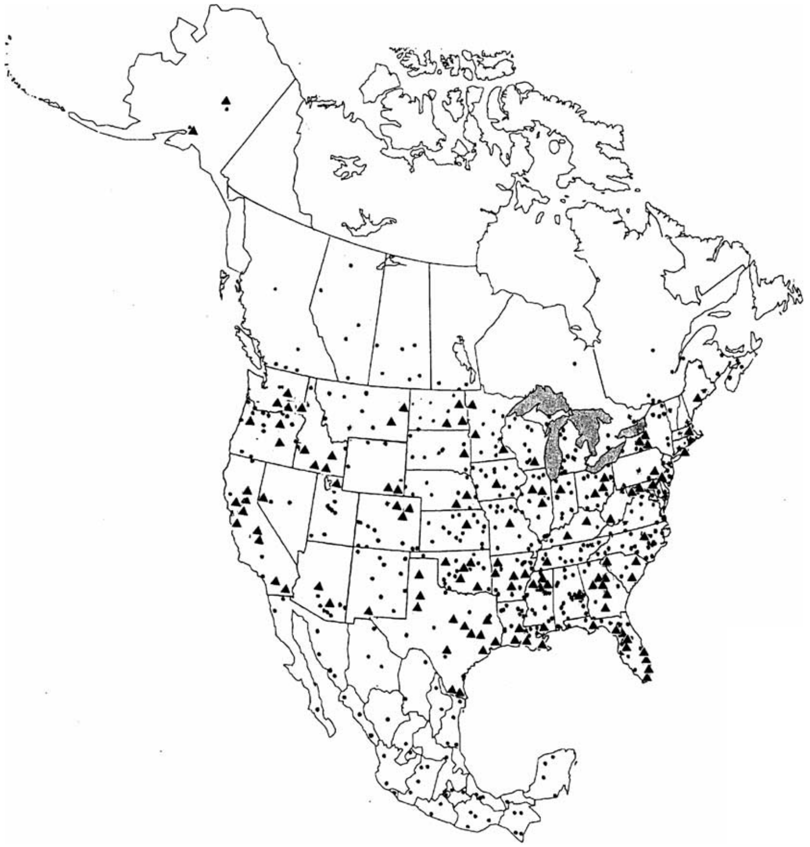

Fig. 3. Distribution of agricultural experiment stations throughout North America. (▲) Indicates research locations of the USDA–Agricultural Research Service (USDA-ARS, 2004). (•) Indicates state/provincial agricultural experiment stations (from CSRS and UGA, 1994).

northwestern USA (cold, dry climate). Soil C sequestration was highest under no-tillage management of cropping sequences that avoided traditional fallow periods. The limited available data suggested that no-tillage management of irrigated crops could sequester SOC at five times the rate of dryland cropping systems under no tillage, an observation that was corroborated by the high soil organic C sequestration rate for no-tillage corn grown under irrigation in Mexico (Follett et al., 2005). The diversity of rangeland conditions in the region suggests a need for more research to obtain reliable estimates of management effects on soil C sequestration. A good-sized database has been assembled on N_2O emission from agricultural soils in the region, with N_2O emission greatest in irrigated cropland and lowest in rangeland ecosystems. Emission of N_2O in the region was related to N input, whether that was inorganic or organic. Methane (CH_4) uptake by dryland soils was generally significant.

The paper by Gregorich et al. (2005) represents the region of eastern Canada and northeastern USA (cold, wet climate). Although distribution of organic C in the soil profile was altered with conservation tillage in this region, the total soil organic C stock did not change when compared with conventional tillage. Nitrous oxide emission has been fairly well characterized in the region with winter/spring thaw events contributing nearly as much as growing season emission. Emission of N_2O was found to be greater in annual cropping systems than in perennial cropping systems. Uptake of CH_4 by soils in the region was positive, but not large.

The paper by Johnson et al. (2005) represents the central USA (moderate climate), often called the breadbasket or Corn Belt of the USA. Soil organic C sequestration with conservation tillage was relatively large in this region. Soil organic C sequestration was even greater in more complex crop rotations than with continuous corn. Cover cropping may be a viable option to further enhance soil organic C sequestration in low-crop-residue-producing systems, but data to support this recommendation are not available. Emission of N_2O and uptake of CH_4 by soils have not been determined to any extent in the region. Despite a significant portion of agricultural land in the region represented by pasture, there are too few data available to assess the effects of management on soil C sequestration and greenhouse gas emission in the region for sod-based systems.

The paper by Martens et al. (2005) represents the southwestern USA (hot, dry climate), where agriculture is generally limited to irrigated croplands and beef cattle production on extensive rangelands. The possibility of altering the large pool of soil inorganic C could have a large implication on global warming potential that is unique from other regions. Several studies have shown that conservation tillage can sequester soil organic C. Traditionally, irrigated land in the region has utilized intensive tillage, and therefore, has shown limited potential for sequestering soil C. Rangeland condition in the southwestern USA has been variably affected by historical overgrazing in the region. Restoration of rangeland with sequestration of C in soils and plants has great potential to restore natural fertility and mitigate further emission of greenhouse gases. The expanding human population in the region will largely determine how water will be distributed among sectors of the economy, which will affect land use.

The paper by Franzluebbers (2005) represents the southeastern USA (hot, wet climate), where a large portion of land previously under agricultural production has been converted back to forests, albeit mostly *Pinus* plantations compared with native hardwoods that once dominated the region. Management of cropland with conservation tillage has been shown to sequester soil organic C at a relatively high rate, especially when conservation tillage systems were maximized in efficiency with the utilization of cover crops for winter biomass production. The warm, moist conditions throughout the year can result in intensive cropping that has beneficial effects on soil organic C accumulation. Conversion of land to pasture was also shown to sequester an even larger quantity of soil organic C than conservation-tillage cropping systems. There is an urgent need to obtain reliable estimates of N_2O and CH_4 emissions from crop and animal production systems in the region.

Table 3 summarizes the major quantitative estimates of historical soil organic C loss, soil organic C sequestration, N_2O emission, and soil CH_4 uptake among the five regions. The lack of estimates for various management comparisons in a region indicates a great need for further research. The concentration of soil organic C in agricultural soil was 22–36% lower than under native condition among the five regions. An estimate of soil organic C sequestration with adoption of conservation tillage was the most complete data set among regions; suggesting significant variation both within and among regions. Soil organic C sequestration with no tillage varied from -0.07 to 0.48 Mg C ha^{-1} $year^{-1}$ among regions. More complex cropping systems led to greater soil organic C sequestration (0.12–0.29 Mg C ha^{-1} $year^{-1}$ among regions) than continuous or simple cropping systems. Other crop management variables were far less investigated, but included significantly greater soil organic C sequestration with cover crops and addition of animal manure and N fertilizer.

Although grazing land is a significant land use in all regions, only limited data were available to estimate the effect of management on soil C sequestration and greenhouse gas emission. Conversion of cropped land to grassland had a large positive effect on soil organic C sequestration in the southern regions, but there were no data available in other regions. Grazing of forage had a large positive effect on soil organic C sequestration in the southeastern USA, but a minor negative effect in the southwestern USA, probably due to differences in precipitation that controlled how fast and to what extent plant communities respond to defoliation. Data from the southwestern USA suggest that even though invasion of grazing lands by leguminous woody plants may not be desirable, this invasion could sequester soil organic C at a greater rate than open grassland.

Nitrous oxide emission was very similar in the northwestern and northeastern regions, averaging 3.2–3.6 kg N_2O-N ha^{-1} $year^{-1}$ in all agricultural systems

Table 3
Summary of soil organic C decline with cultivation, soil organic C sequestration, N_2O emission, and soil CH_4 uptake in response to agricultural management among five regions in North America

Management comparison	Region in North America[a]				
	Northwest	Northeast	Central	Southwest	Southeast
Decline in soil organic C concentration from native condition (%)	34 ± 14	22 ± 10	NA	25 ± 33	36 ± 29
Soil organic C sequestration (Mg C ha^{-1} $year^{-1}$)					
No tillage versus conventional tillage	0.27 ± 0.19	-0.07 ± 0.27	0.48 ± 0.59	0.30 ± 0.21	0.42 ± 0.46
More complex cropping systems	0.12 ± 0.10	NA	0.18 ± 0.25	0.29 ± 0.17	0.22 ± 0.33
Addition of animal manure	0.15 ± 0.02	NA	NA	NA	0.72 ± 0.67
Addition of N fertilizer	0.09 ± 0.08	NA	NA	NA	0.18 ± 0.35
Conversion of cropped land to grass	0.94 ± 0.86	NA	0.56 ± 0.60	0.32 ± 0.50	1.03 ± 0.90
Grazed versus ungrazed grassland	0.16 ± 0.12	NA	NA	-0.03 ± 0.15	0.76 ± 0.60
Invasion of woody plants into grassland	NA	NA	NA	0.22 ± 0.50	NA
N_2O emission (kg N_2O–N ha^{-1} $year^{-1}$)					
All agricultural systems	3.0 ± 7.2	3.2 ± 5.6	NA	7.2 ± 20.8	NA
Crop systems	3.8 ± 8.1	3.7 ± 6.1	NA	NA	NA
Grass systems	0.6 ± 1.5	1.2 ± 1.4	NA	7.2 ± 20.8	NA
N_2O emission factor with added fertilizer					
Background (kg ha^{-1} $year^{-1}$)[b]	0.9	0.8	NA	NA	NA
Proportional rate (% of added fertilizer N emitted)[b]	1.9	1.2	NA	NA	NA
CH_4 emission by soil (kg CH_4–C ha^{-1} $year^{-1}$) (negative value indicates uptake)					
All cropping systems	-1.4 ± 0.8	-0.3 ± 0.3	NA	1420 ± 1735	NA

[a] Data from regions were obtained in the articles appearing in this issue, i.e. Northwest, western Canada and northwestern USA, Liebig et al. (2005); Northeast, eastern Canada and northeastern USA, Gregorich et al. (2005); Central, central USA, Johnson et al. (2005); Southwest, southwestern USA, Martens et al. (2005); Southeast, southeastern USA, Franzluebbers (2005).
[b] Background N_2O emission represents the y-axis (b) and proportional rate represents the slope (a) from the equation: $y = ax + b$.

measured. The portion of added fertilizer N that was emitted as N_2O-N varied from 1.2 to 1.9% in these two regions, which was similar and higher than the IPCC coefficient of 1.25% of unvolatilized N inputs (IPCC, 1997). An estimate of CH_4 uptake by soil, mostly from cropland, was available only from the northwestern and northeastern regions, averaging 0.3–1.4 kg CH_4–C ha^{-1} $year^{-1}$ in all agricultural systems investigated.

Although many scientific investigations have been conducted during the past century of agricultural research in North America, there are still significant gaps in our knowledge about how management can simultaneously (1) satisfy the economic livelihoods of the farmers that cultivate our land, (2) reduce the threats to the environment from unintended consequences of our human need to produce food and fiber, and (3) improve the quality of the land for generations to come. It is our hope that the summarized information and extensive citations contained in this special issue will serve as a platform to organize new research aimed at (1) quantifying the effects of a wide range of agricultural management systems on soil organic C sequestration and greenhouse gas emission, (2) developing robust recommendations for improving soil, water, and air quality in North America, and (3) developing novel approaches and unique perspectives in managing agricultural land to achieve both production and environmental goals.

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